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EXPERIMENTAL SURFACE SHAPE RECONSTRUCTION USING MICROPHONE ARRAYS

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ABSTRACT

The sound field scattered by a smooth rough surface, and recorded by multiple microphones, can often be modelled by means of an underdetermined system of equations, obtained from boundary integral equations resolved at the surface with Kirchoff approximation. The same underdetermined system can be inverted, yielding an estimate of the surface shape. Regularisation techniques are applied to the inverse problem. In this work, the procedure is validated experimentally on a set of acoustically rigid surfaces. In contrast with previous tests, where a single microphone was used to scan a rough surface along an arch, in this study an array of up to 34 microphones arranged on a plane parallel to the surface has been used. Furthermore, multiple frequencies of excitation in the range 10-25 kHz have been tested simultaneously using a broadband source. Uncertainties involved in the measurements are discussed. In particular, the uncertainty associated with differences in the response between microphones has been addressed by means of a calibration performed in situ over a flat rigid surface. The plane array configuration is demonstrated to be an equally effective but potentially more versatile alternative to the curved array solution. The effects of the choice of frequency on the resolution and robustness of the reconstruction are highlighted.

1. INTRODUCTION

The sound produced by a point source with vector coordinates $\boldsymbol{S}$ is scattered by a smooth, acoustically rigid, two-dimensional surface $z(x)$ of finite but large size, and measured at multiple receivers $\boldsymbol{R}_m$. If $\boldsymbol{S}$ and $\boldsymbol{R}_m$ are in the surface far-field, the complex pressure amplitude can be calculated with the Kirchhoff approximation as [1]

$$p(\boldsymbol{R}_m) = \int H(\boldsymbol{S}, \boldsymbol{R}_m, x) \exp\left[-\mathrm{i}q(\boldsymbol{S}, \boldsymbol{R}_m, x) z(x)\right] \mathrm{d}x, \tag{1}$$

where the functions H and q are described in [1]. Neglecting the dependence of q by $\boldsymbol{R}_m$, $q(\boldsymbol{S}, \boldsymbol{R}_m, x) \approx \hat{q}(\boldsymbol{S}, x)$, Eq. (1) can be approximated by a linear, usually underdetermined system [2, 3],

$$\mathrm{P}_{N_R \times 1} = \mathrm{H}_{N_R \times N_x} \mathrm{f}_{N_x \times 1}, \tag{2}$$

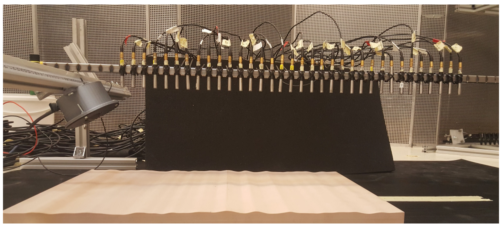

Figure 1. Measurement setup. The speaker is on the left.

where N_R is the number of receivers, N_x is the number of points that discretise the surface, and $\mathrm{P}_m = p(\boldsymbol{R}_m)$ and $\mathrm{f}_n = \exp\left[-\mathrm{i}\hat{q}(\boldsymbol{S}, x_n) z(x_n)\right]$ are the elements of vectors P and f, respectively. Eq. (2) can be inverted numerically [2, 3]. As a result, the shape of the scattering surface can be reconstructed from the measurement of the acoustic field at $N_R < N_x$ locations. The only previous experimental validation of the technique employed sequential measurements along an arch by a single microphone [3].

2. METHODS

Here, the method is applied to an array of 34 1/4” microphones arranged in line with a spacing of 20 mm. The line array is simpler and more practical than the arch. The microphones and source were at a height of 270 mm and 200 mm from the surface, respectively. The measurement setup is shown in Fig. 1. The speaker was inclined at 60° from the horizontal, and produced a white noise with frequency $\leq$ 25 kHz. The scattering surface was machined from a block of Medium Density Fibreboard (MDF) material, and had a known random profile $z(x)$, with 1 mm standard deviation, and with a power-function spectrum $\propto \lambda^5$ for 5 mm$\leq \lambda \leq$ 50 mm, where λ is the surface wavelength.

The technique is sensitive to microphone positions uncertainties [2]. Additionally, the microphones used for this test were not phase-matched. To reduce these uncertainties, the following procedure was adopted: (i) the reflection from a flat surface was modelled ($p_0(\boldsymbol{R}_m)$) with Eq. (1) at each microphone location and for 301 frequencies f between 10 kHz and 25 kHz; (ii) the same quantity was measured ($\tilde{p}_0(\boldsymbol{R}_m)$), by turning the scattering sur-

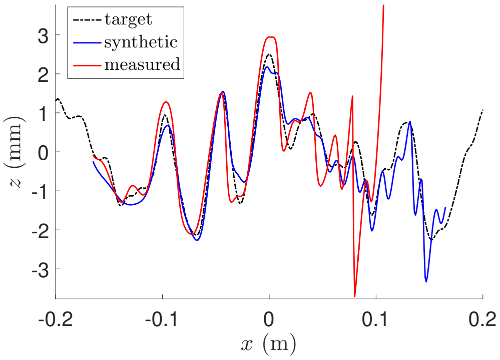

Figure 2. Surface reconstruction, $f = 18\ kHz$.

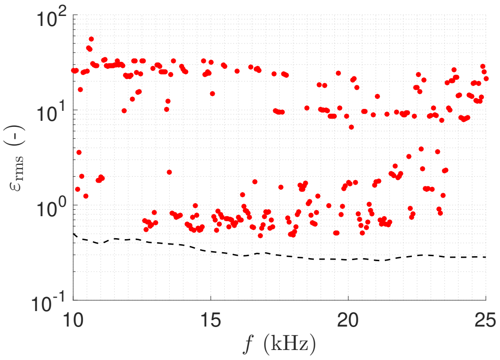

Figure 3. Rms relative surface reconstruction error. Synthetic (black line) and measured (red dots) data.

face face-down and calculating the complex amplitude by means of an FFT; (iii) a calibration factor was calculated as $\Gamma(\boldsymbol{R}_m) = p_0(\boldsymbol{R}_m)/\tilde{p}_0(\boldsymbol{R}_m)$; (iv) the measurement was repeated with the rough surface facing upwards, and the resulting pressure distribution was multiplied by Γ. To isolate the effects of the numerical inversion, which yield a lower bound to the uncertainty of the reconstruction, an ideal case was simulated by generating synthetic data by means of Eq. (1) applied to the known surface geometry.

3. RESULTS

Fig. 2 shows an example of surface reconstruction obtained from the FFT at 18 kHz, from the measured and synthetic data, compared to the known 'target' surface geometry. The accuracy of the reconstruction appears reasonable, especially in the central part of the surface. The rms error relative to the surface standard deviation, calculated for each frequency in the central part of the surface (-0.19 m $\leq x \leq$ 0.03 m) is shown in Fig. 3. While the error obtained with the synthetic data decreases smoothly with the frequency from 50 % to 28 %, the experimental error fluctuates vigorously, with complete failure ($\varepsilon_{\mathrm{rms}} > 5$) occurring more often at lower and higher frequencies. The minimum rms-averaged error obtained experimentally is ~ 0.5.

Fig. 4a shows the comparison between the spatial spectra of the 'target' and reconstructed surfaces, calculated for f =18 kHz. Good agreement was found at wavelengths $>$ 40 mm. The spectrum was overestimated at higher wavenumbers, especially for the measured data. The difference between 'target' and 'synthetic' spectra is shown in Fig. 4b, for all frequencies. Surface scales larger than approximately twice the acoustic wavelength were reconstructed accurately ($\pm$3 dB), while larger errors were found for shorter scales. The theoretical horizontal resolution improves with the frequency. However, uncertainties of the experimental data are higher at higher frequencies, often causing the failure of the method. Broadband signals may be used to improve the robustness of the method, by combining the information across different frequencies.

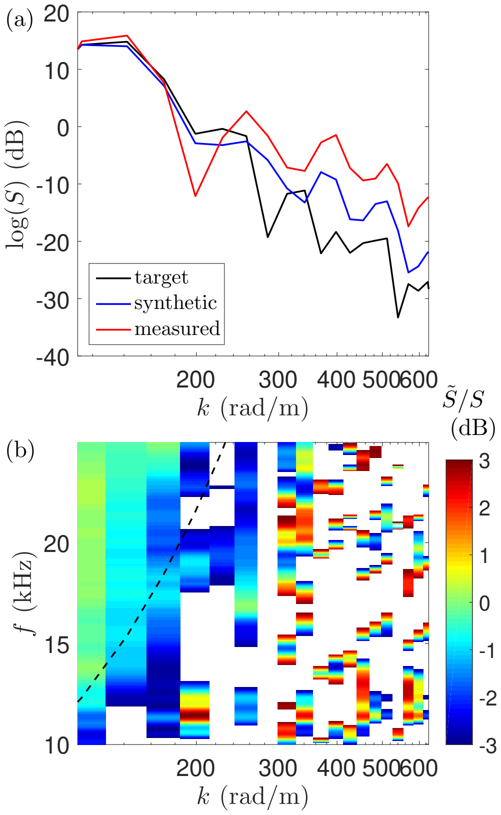

Figure 4. (a) Surface power spectrum, for f = 18 kHz. (b) Spectrum reconstruction error, based on synthetic data. (dashed line) $k = (2\pi f/c_0)/2$.

4. ACKNOWLEDGMENTS

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5. REFERENCES

[1] F. G. Bass and I. M. Fuks, *Wave Scattering from Statistically Rough Surfaces*. Pergamon, Oxford, 1979. p. 186.

[2] A. Krynkin, K. V. Horoshenkov, and T. Van Renterghem *J Acoust Soc Am*, vol. 140, no. 3, 2016.

[3] A. Krynkin, G. Dolcetti, and S. Hunting *Rev Sci Instrum*, vol. 88, no. 2, 2017.